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RIGID CULVERTS UNDER HIGH OVERFILLS

by R. Robinson Rowe, M. ASCE

HIGHWAY DIVISION

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RIGID CULVERTS UNDER HIGH OVERFILLS[1]

R. Robinson Rowe,[2] M. ASCE

SYNOPSIS

Progressively higher standards for highway width, alignment, gradient and durability have been a challenge to designers of cross-drainage facilities. Relatively cheaper earthwork favored culverts instead of bridges. Extrapolation of low-fill culvert practice to high-fill requirements would have meant long barrels of great unit cost. Adaptation of the earth arch to relieve culverts of part of the load promised a substantial reduction in cost. Experimental at first, this practice has now been justified by satisfactory performance. Review of performance disclosed occasional distress, which can be obviated by more careful attention to detail. The paper summarizes the progressive developments in design and reports the findings of a field review of performance, including suggestion for further development of the practice.

INTRODUCTION

Fifty years ago, few culverts were more than timber boxes close below an earth or gravel road, the exceptions being masonry arches of stone or brick. Rarely did spans exceed 12 ft or overfills 5 ft; for a wider stream or deeper gulch, bridges were cheaper.

Highways have grown sensationally with the years. (Figure 1) Modern standards of alignment and gradient aided by heavier and more efficient earth-moving equipment have led to high embankments, many of them over 100 ft and some approaching 200 ft in height. Culvert lengths have increased even more because of precautionary terracing of the higher embankments and skewness of highway with respect to lines of cross drainage.

Culverts became more desirable than bridges for such locations because the alternation of fills in gulches with cuts thru the spurs balanced earthwork on a lower and more economical profile and facilitated continuity of construction operations. However, the culvert had to equal the bridge alternative in permanence, and exceed it if possible because of the impracticability of replacing a deficient culvert in a deep fill.

It was expedient, at first, to design by adaptation of low-fill types to higher and higher limits, simply by specifying greater strength for conduit walls (Figure 2a). This limited pipe culverts to 40-ft fills, but cast-in-place boxes or arches could be designed for more. Multiple-cell culverts (Figure 2b) could be used if debris was light or controllable.

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1. Paper read at ASCE Convention, San Diego, February , 1955.
2. Bridge Research Engr., California Div. of Highways, Sacramento, Calif.

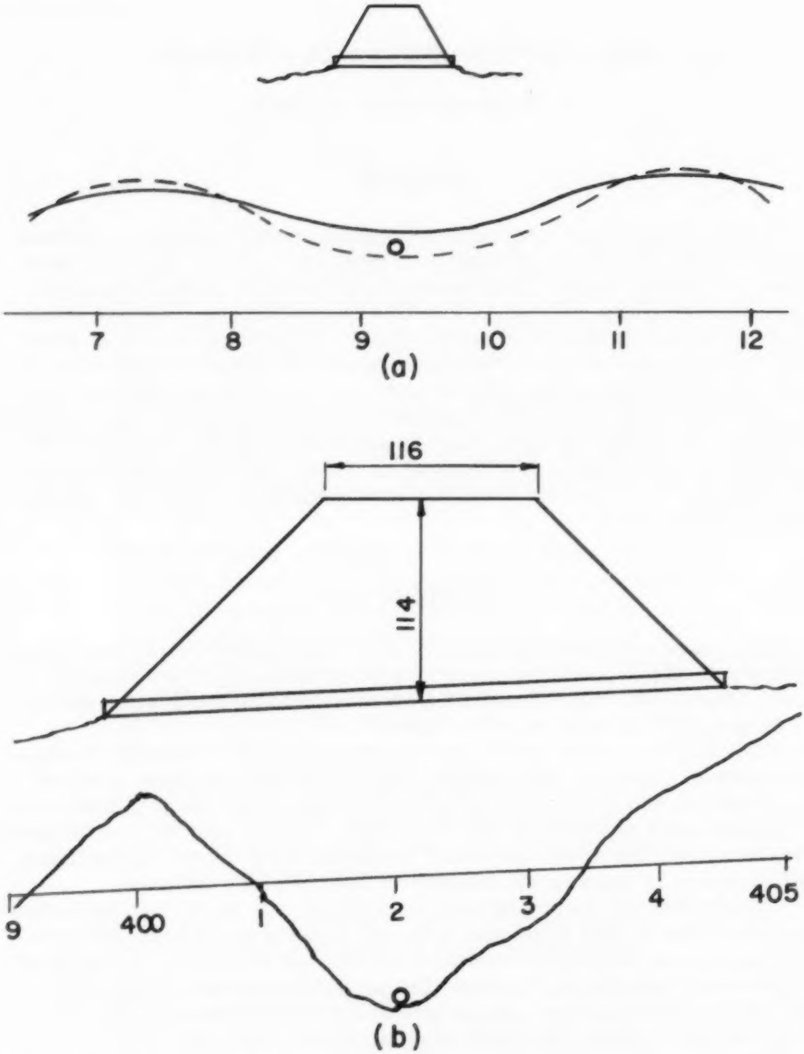


FIG. I- Culverts 50-yr. ago (a) were short under low fills of rolling grades, but modern highways (b), on high-speed alignment and grade, require long culverts under high overfills.

(a) HEAVIER SECTION

(b) MULTIPLE CELL

(c) STRUTTING

(d) FLOATING SLAB

(e) YIELDING BASE

(f) LOOSE OVERFILL "METHOD B"

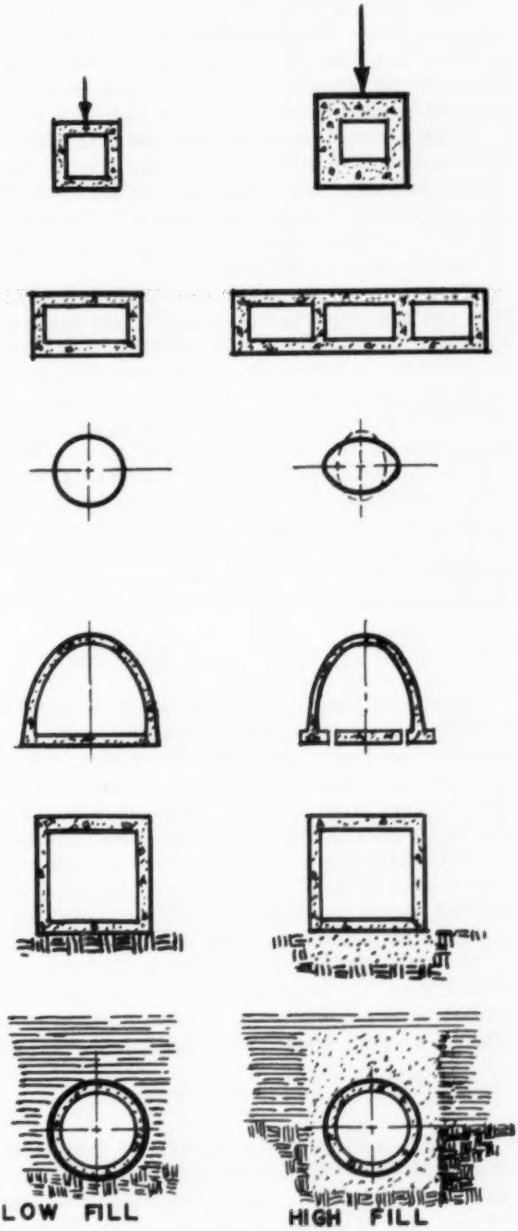


FIG. 2 ADAPTATION OF PRACTICE TO HIGHER OVERFILL

When extrapolation became expensive, other expedients were often cheaper. On a steep mountain stream, the culvert could be run on a mild gradient in a side-hill location to a chute on the face of the downstream embankment, greatly reducing maximum overfill. For crooked channels, a tunnel might be cut on a direct line thru solid material.

Since a tunnel lining is designed more from the character of the soils surrounding it than from the weight of soil above it, the principle was adaptable to culverts. For example, the fill could be built first and then tunnelled for the culvert. Or the fill could be built over arched falsework, leaving space for a future culvert. In either case, the embankment would become an earth arch on a large scale.

To avoid the expense of tunnelling or falsework, an intermediate adaptation was developed to carry part of the load on an earth arch and part on the culvert structure. This could be done by building the culvert to yield as the fill was built over it, just as flexible culverts (Figure 2c) were cambered by struts and yielded when struts were removed. Rigid culverts (Figure 2d, e, f) were built on yielding foundation or roofed with yielding overfill. To some degree, the tunnel analogy is applicable to any such scheme.

This paper is limited to rigid culverts, reporting first the standard designs adopted by the California Division of Highways for RC arches, pipe and boxes with the overfill limits applicable to each, then the observations of performance of typical installations and finally some conclusions on reliability of design, mistakes responsible for local overstress and modifications of design and construction to avoid such mistakes.

Arch Design

As adopted, the standard RC arch culvert (Figure 3) has a 3-centered barrel, designed to minimize tension, supported on narrow wall footings. Under heavy loads, the foundation yields, the entire barrel subsides, and an earth arch develops over the crown. The wall footings are held apart by a floating invert slab. If subsidence of the arch transmits pressure under the invert slab, it moves upward to relieve the pressure.

Articulation is provided by building slab and footings continuous and the arch barrel in 30-ft segments. Struts are left to support the barrel until overfill equals the span. The first overfill, up to 25% of the span, is loosely compacted to provide an additional zone of yielding material.

The same geometric shape is used for spans of 6 to 22 ft (areas from 27 to 363 sq ft). Minimum overfill is nominally the span and maximum overfill is nominally 60 ft, but these limits can be exceeded by adding a relatively small amount of reinforcement (Plate A).

Pipe Practice

Rigid pipe for highway culverts is practically limited to reinforced concrete pipe. During the period of rapid extrapolation of height of overfill and length of culvert, commercial pipe was improving in quality and uniformity, due to decentralization of centrifugal casting yards. It became economical to use larger sizes because this decentralization reduced cost of haul to the site and the rapid increase in cost of field labor generally favored prefabrication.

Bedding practice received early attention. Figure 4 summarizes four distinct combinations of bedding and backfill influential in determining

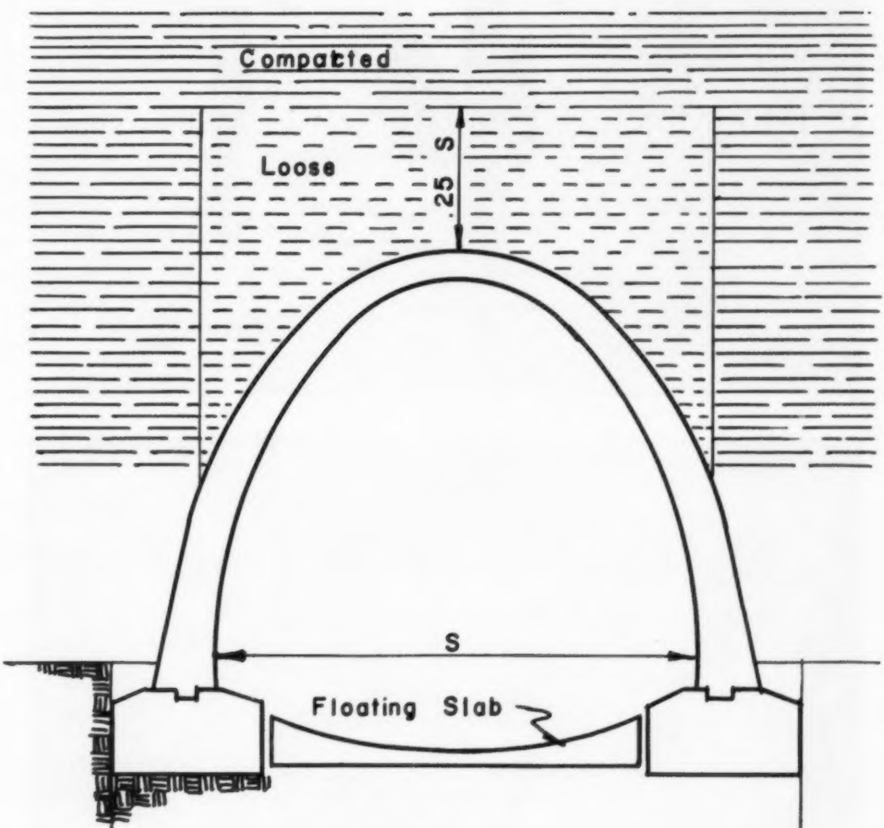
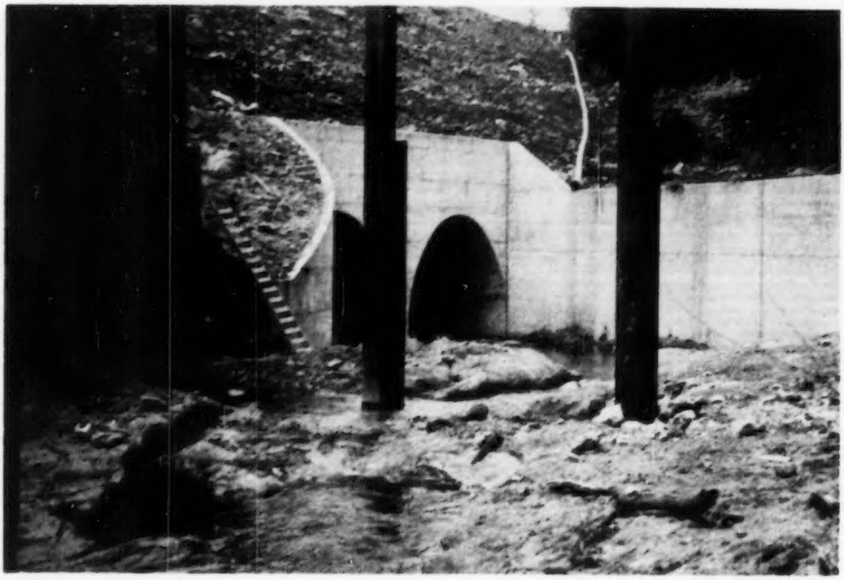


FIG. 3 - Floating slab and loose or uncompacted backfill reduce pressure on extrados of arch.



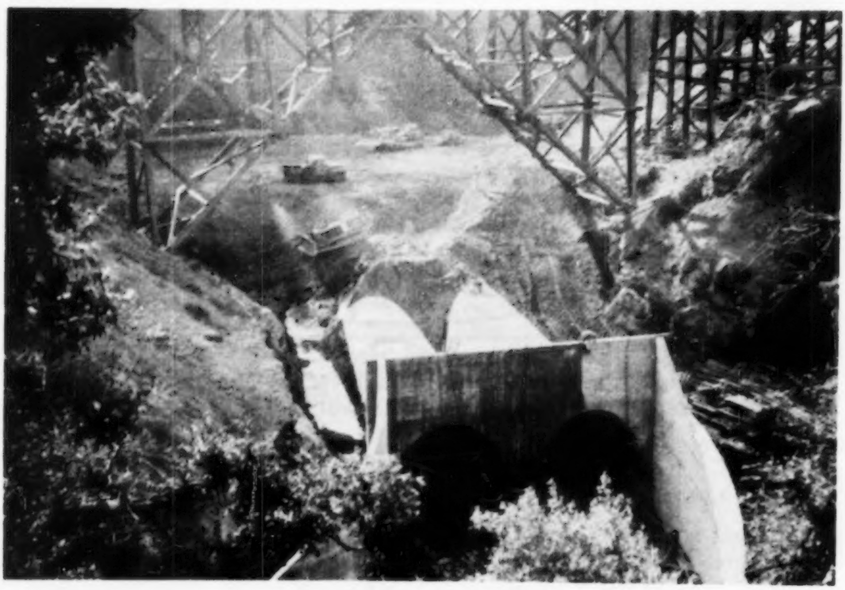


PLATE. A

allowable overfill. Details are beyond the scope of this paper, except to report the objective of a uniformly yielding bed, often obtained by sub-excavation and imported borrow. This is easier to inspect and control than a meticulous shaping of the bed to fully cradle the pipe.

Reappraisal of pipe strength was the second step in design for higher overfills. Specifications for standard and extra-strength pipe govern the wall thickness, strength of concrete and amount of reinforcement in such a way that the resulting pipe strength exceeds the test strength. Overfill limits were computed for the dependable strength of each commercial pipe.

For design beyond these new limits, experiment was started in 1943 with "Method B Backfill" (Figure 5) which is an application of the tunnel analogy to reduce the pressure on the top of the culvert. Reduction in pressure is obtained by specifying two degrees of compaction for the embankment—loose compaction above the culvert for a height equal to the culvert span (or diameter) and dense compaction for the rest of the section.

The mechanics of reduced pressure can be visualized in several ways. From the tunnel analogy, the loose backfill and a small segment of earth marked "Unstable" become a part of a "tunnel" and the compacted zone above its intrados subsides just as the rock crown of a tunnel deflects when the supporting rock is removed. When the distance AB is small, the earth structure is analogous to an arch, for which the zone of loose earth is the false-work which has been struck but not removed.

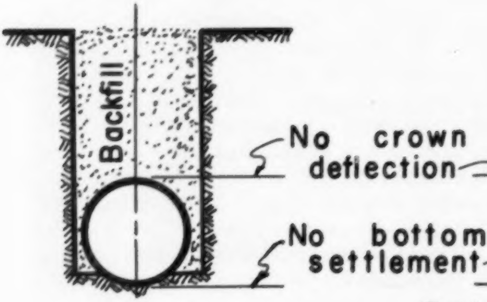
The subsidence of the compacted overfill, being greater than the compacted side-fill, develops vertical shear along the boundary. Along the haunch plane AB, shear resistance should be adequate to support W, the weight of half the overfill, plus a live load P. Hence there must be a minimum distance AB or the earth arch will fail in shear. The generalized shear distribution curve at the right shows that maximum vertical shear will exceed twice the average. It is based qualitatively on the Mohr circles for A, M and B, which show that shear must be zero at A and B where there is no horizontal compression.

After this appeared successful, the method became a standard alternative. An abstract from design tables (Table 1) shows the limitation of the conventional Method A and the chart (Fig. 6) is a guide to economy in its use. It must be understood that Method B is not a cheap expedient, because it interferes with continuous operations in constructing large embankments with heavy machinery, so Method A with heavy pipe is usually selected up to the limit for commercial pipe. Method B is used for overfills exceeding 60 ft for small and 33 ft for large pipe, limited as shown for diameters exceeding 81 in. Monolithic pipe has been designed for higher fills (Plate B).

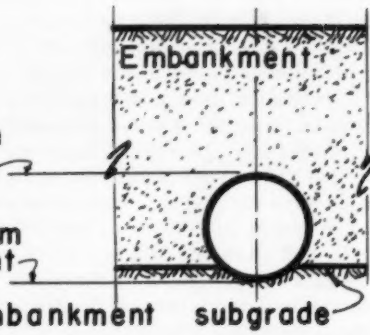
Box Design

The RC box has always been a popular design for culverts, but it lagged behind arches and pipe in adaptation to high overfills. Up to a practical limit, walls and slabs were made heavier. Next, working stresses were raised on the theory that dead loads do not need as large a safety factor as live loads. Finally, from the tunnel analogy, particular attention was given to bedding and Method B backfill specified as an alternative.

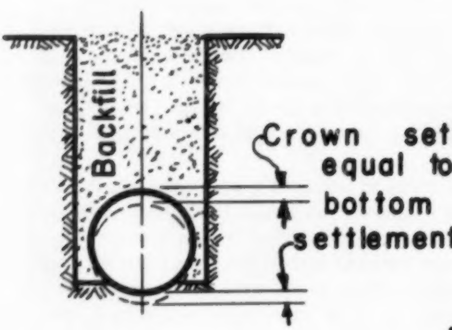
Box culverts ranging in size from 4x2 to 12x12 ft have been standardized with several strengths designed for each size. The standard drawing includes for each structural section an overfill limit for each of 4 combinations of bedding and backfill, one of which is equivalent to Method B backfill for rigid pipes.



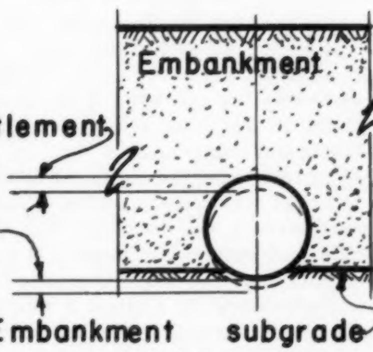
CASE II
Rigid culvert in trench, unyielding foundation.



CASE VI
Rigid culvert under embankment, unyielding foundation.



CASE IV
Rigid culvert in trench, yielding foundation.



CASE VIII
Rigid culvert under embankment, yielding foundation.

FIG. 4- Of 4 important bedding situations, Case IV is most favorable, Case VI the least.

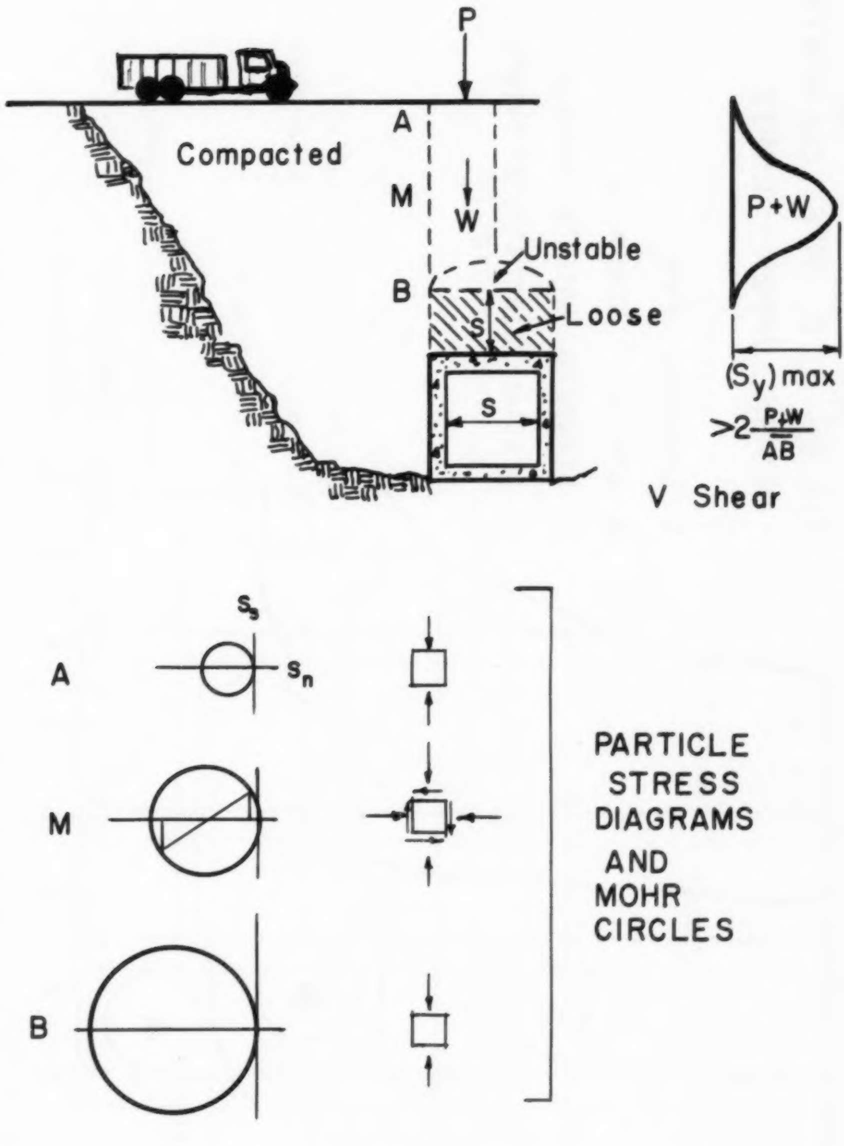
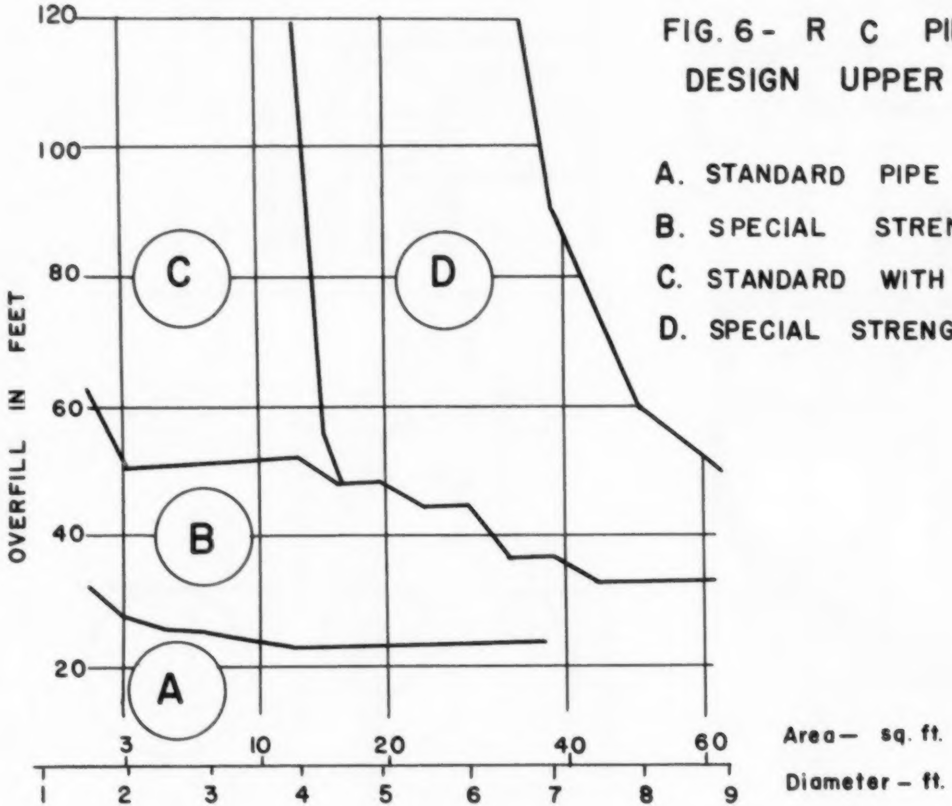


FIG. 5
Method B backfill reduces load on culvert if overfill height is sufficient to resist shear.

FIG. 6 - R C PIPE CULVERTS DESIGN UPPER LIMITS

A. STANDARD PIPE
B. SPECIAL STRENGTH
C. STANDARD WITH "B" OVERFILL
D. SPECIAL STRENGTH, "B" OVERFILL



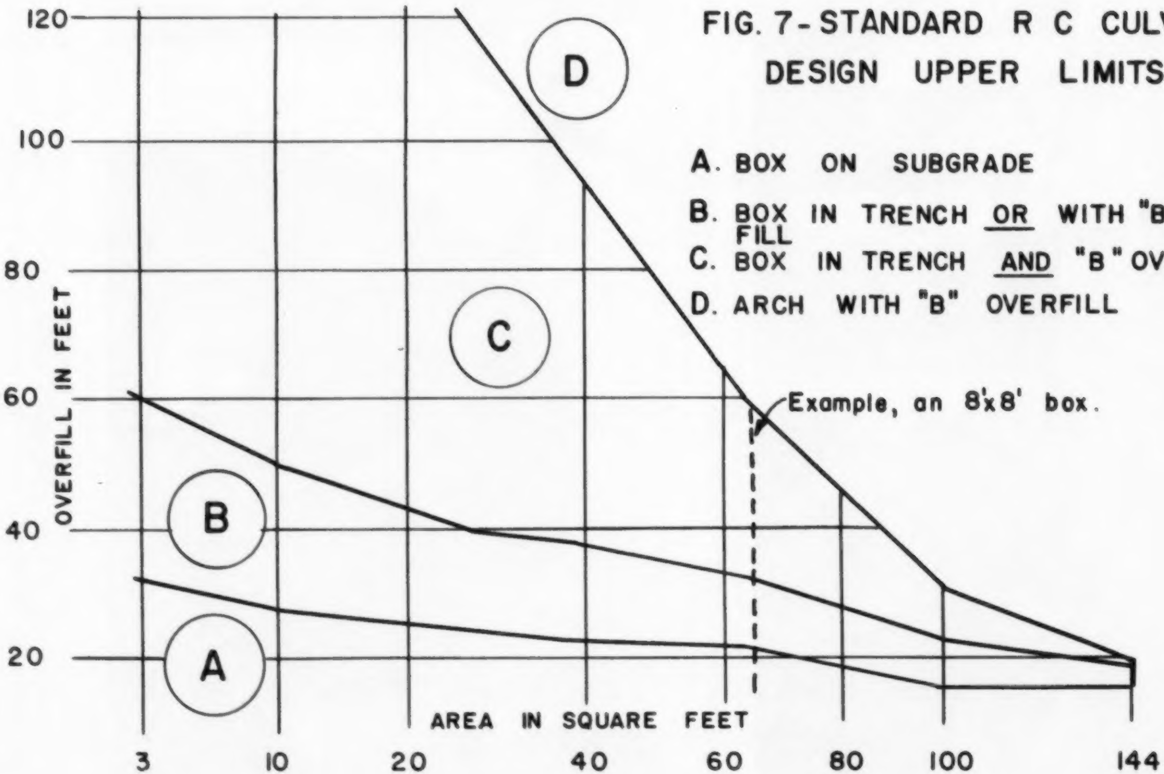


FIG. 7 - STANDARD R C CULVERT DESIGN UPPER LIMITS

A. BOX ON SUBGRADE

B. BOX IN TRENCH OR WITH "B" OVERFILL

C. BOX IN TRENCH AND "B" OVERFILL

D. ARCH WITH "B" OVERFILL

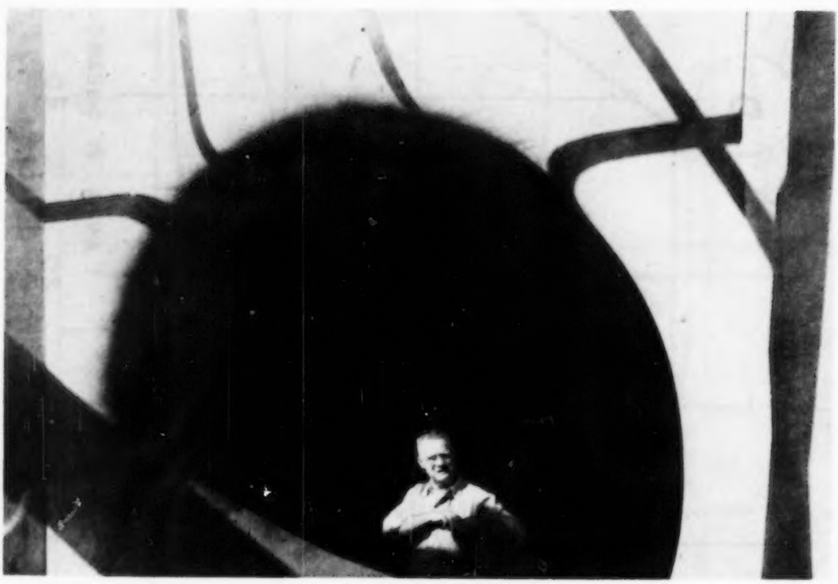


PLATE. B

The upper limits of design with and without Method B are shown in Figure 7. Using an 8x8 box with an area of 64 sq ft as an example, the strongest standard section would only support 22 ft of overfill (A), but the limit is extended to 32 ft by using Method B backfill or by building the box in a trench (B). Further extension to 58 ft is possible by combining these two devices (C), but arch culverts would be used (D) for fills exceeding 58 ft. If natural ground is not satisfactory for ordinary entrenchment, an imperfect trench can be dug in a partially completed and well compacted embankment.

In all extension of practice to high overfills, with either flexible or rigid culverts, it is most important that there be uniform foundation under the bedding to avoid large differential settlement when the foundation is compressed by the heavy earth load. High fills mean long culverts, usually too long for the culvert to follow a sinuous channel. If the direct line and grade from channel intercepts on each side of the embankment resembles that shown in Figure 8, uniform foundation can usually be obtained by (a) deflection of line to one side of the channel, or (b) depression of grade below natural bed of the stream.

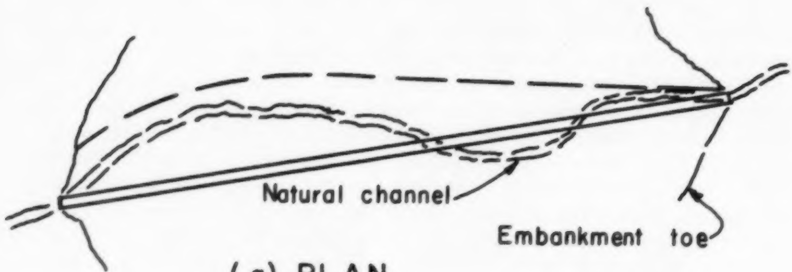
Performance Inspection

Periodic inspections were made in the early life of all installations on an experimental basis. With few exceptions, the observations were favorable, the method was adopted for standard installations and thereafter inspections were essentially limited to those required for maintenance. Large culverts classed as bridges were an exception, for these were inspected regularly for structural deficiencies or distress.

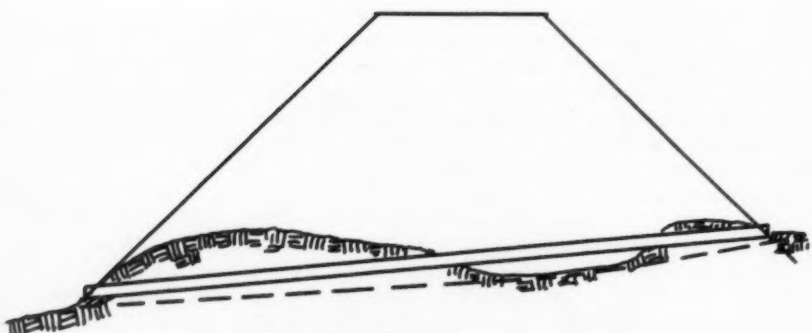
In August 1954, prompted by collateral interest of others, a joint review was made of rigid culverts under high overfills in the northern part of California. The results were so informative that the review was extended into Southern California in November. Figure 9 shows the region covered by the survey, but it should be added that most of the indicated locations represent several culverts in the same area.

Culverts selected for the review (Fig. 10) ranged from a 36-in pipe under a 111-ft overfill to a 120-in pipe under an 83-ft overfill. The largest section was a double 18-ft arch under a 70-ft fill. The longest was 1400 ft of 60-in RC pipe under a 65-ft fill, of which the central 1045 ft had been installed by Method B. The detail of procedure was varied with the findings of a preliminary superficial examination. If there were signs of distress, measurements were made of visible evidence, such as cracking and joint separation. Where found, position of the T marking top of elliptically reinforced pipe was recorded. Photos were taken of a few typical and all extreme conditions. On the other hand, if there were no obvious signs of distress, the record was a qualitative appraisal of the average condition.

On the whole, the performance of all types of rigid culverts justified the adopted practice. Least distress was found in arches and one large monolithic pipe; the most in a box section. Method B installations were generally in excellent condition, independent of depth of overfill, but pipes installed under ordinary backfills were distressed somewhat in proportion to depth. In a few cases a long culvert would be found in excellent condition except for one or two signs of local distress; these were hard to explain except as mistakes in construction and supervisory inspection. Where distress was uniform or consistent, the cause could be found. The principal causes will be discussed in a concluding analysis.



(a) PLAN



(b) PROFILE

FIG. 8- Indirect line or grade to develop uniform foundation.

FIG. 9 - CULVERTS VISITED DURING REVIEWS OF AUGUST AND NOVEMBER 1954

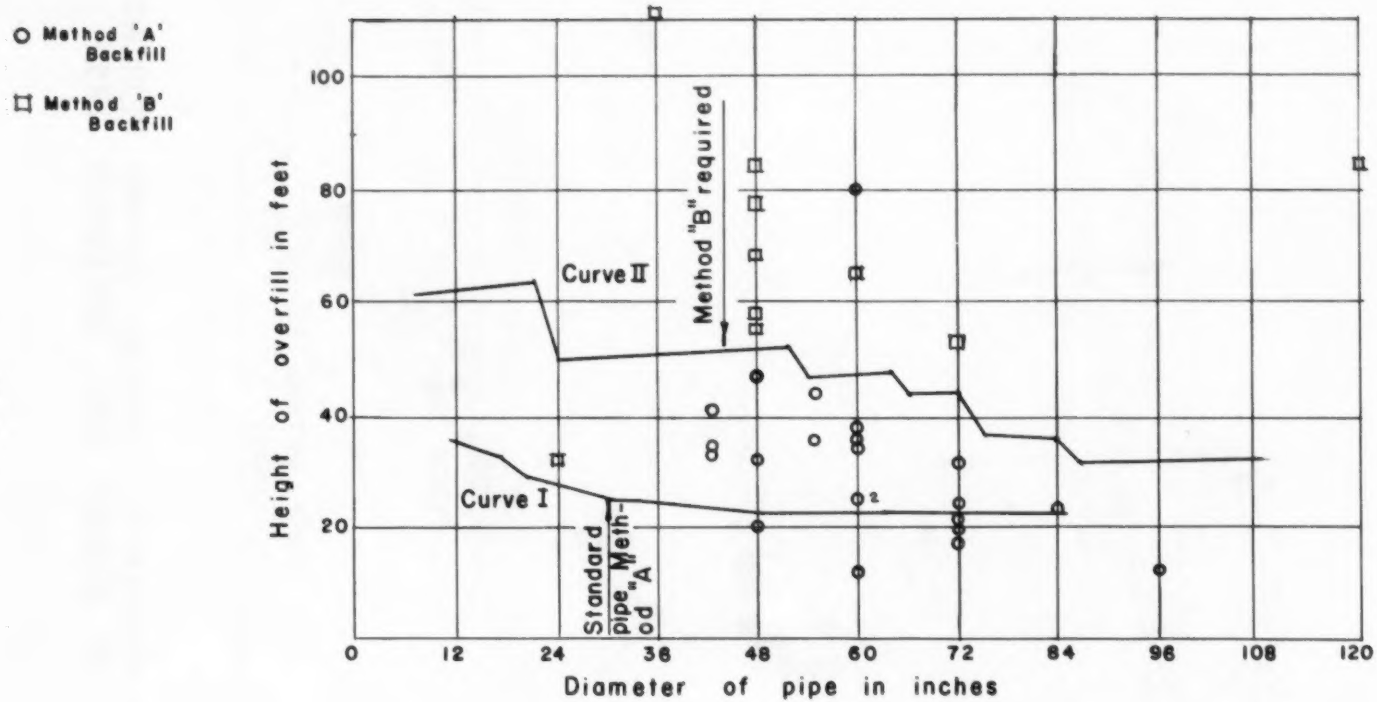


FIG. 10 - Between Curve I & Curve II, there is a choice between Method B and Method A with stronger pipe.

By far the most common departure was the opened joint between pipe sections (Plate C). Openings were largest near ends of culverts. This was ascribed to elongation of the culvert by spreading of the fill (Figure 11) as it subsided under load. Standard joints have little tension value, so elongation was concentrated rather than distributed thru the pipe. Spreading of high fills being the rule rather than the exception, due to a combination of lateral flow of plastic earths and a Poisson effect in elastic elements, joint openings are tolerable displacements and not distress. If not tolerable in a particular location, openings can be prevented by (1) secure anchorage of headwalls, (2) joint design to carry tension, (3) location of culvert in solid material, or (4) deferring joint seals until the embankment is completed. The writer prefers the last remedy and believes it should be standard practice for all large pipes.

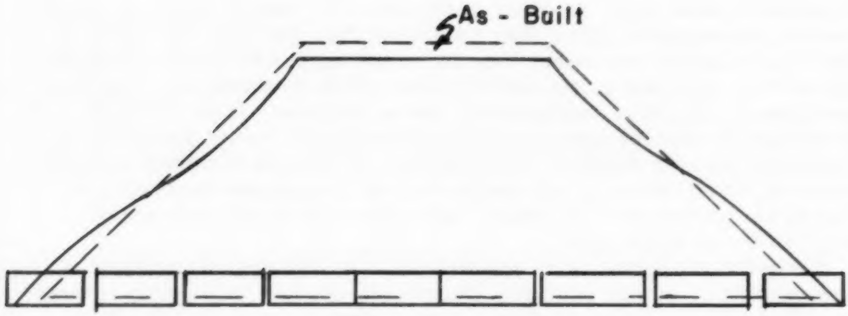
Related to the spread of an embankment is the longitudinal creep of an embankment on a steep gradient. (Figure 12). Such an explanation seemed most logical for a longitudinal crack which appeared in the uphill side of two segments of an otherwise flawless culvert. Obviously, if principal stress is deflected from the vertical by creep of the fill, maximum tension will not occur at crown of pipe, but on the uphill side, where tensile resistance is less in elliptically reinforced pipe. Altho the single occurrence may not justify a remedy, inner and outer cages of circular reinforcement could be specified for pipes in such locations.

Next to open joints, the most common departure was the longitudinal cracking of the crown of pipe, occasionally accompanied by corresponding cracks along the invert. Cracking to some degree in these locations is a normal expectancy, because tension is a maximum and elongation of tensile reinforcement stretches the surrounding concrete beyond its low value in tension (Plate D). In the best pipes, the cracking should be distributed in fine hair lines, but any departure from homogeneity in concrete or bond concentrates the elongation in a single wide crack.

The single wide crack may not indicate greater distress than a manifold of hair cracks, but it can lead to real distress and ultimate failure if it admits corrosive air or water to the embedded steel. Hence one remedy is to seal the cracks, particularly those on the invert, with a flexible adhesive crack filler or invert pavement. Pre-stressed pipe, of course, would probably not crack in this way; if commercially available, it should be considered for difficult locations.

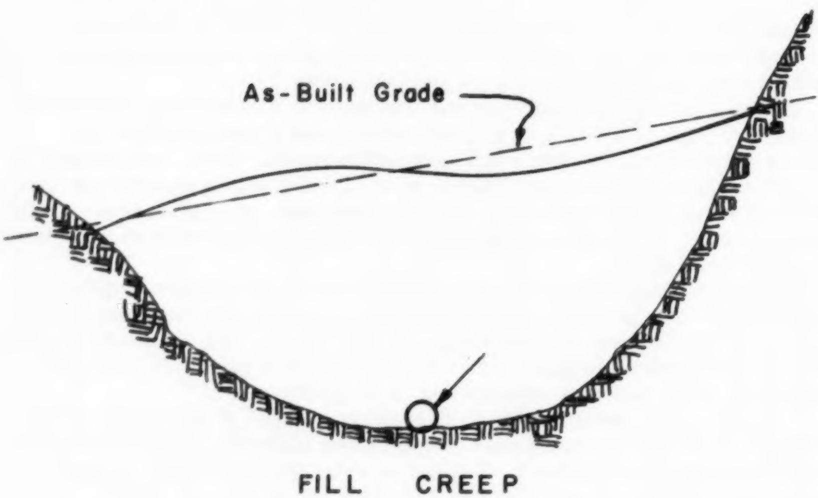
Perhaps all locations under high overfill should be considered difficult, with the difficulty generally proportional to the height, but there are other factors which increase the probability of distress for even moderate heights. Two, in particular, are plasticity of fill material and presence of ground water, the latter probably contributing to the former.

If ground water saturates the zone of loose backfill, it will transmit full pressure from the overlying zone of compacted material, compromising the earth arch and tunnel analogy. Two cases were observed where ground water was entering the pipe (Figure 13) about 100 ft from the upper end; there was no unusual distress in the dry section, but cracks up to 0.09" in the crown of the wet pipe. Distress was much greater in (b) with 41 ft of overfill placed by Method A than in (a) with 77 ft of overfill placed by Method B. Probably the saturated fill had become plastic and increased the load on the pipe by unusual subsidence and a higher unit weight. Actually this possibility had been foreseen and underdrains provided, but those had fouled. The remedy may lie in perforation of the upper half of the culvert



FILL STRETCH

FIG. 11 - Elastic and plastic deformation of the fill and supporting soil opens the joints of segmented culverts.



FILL CREEP

FIG. 12 - Plastic creep of an unsymmetrical fill may cause higher pressure on side of culvert than on the crown.

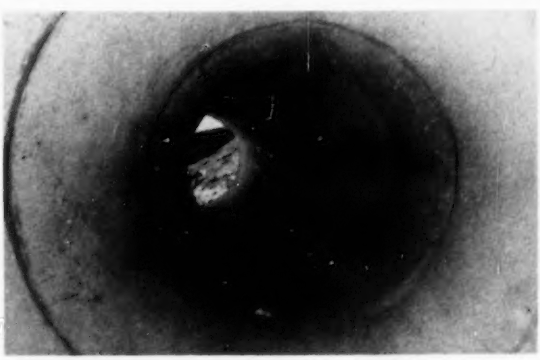


PLATE. C

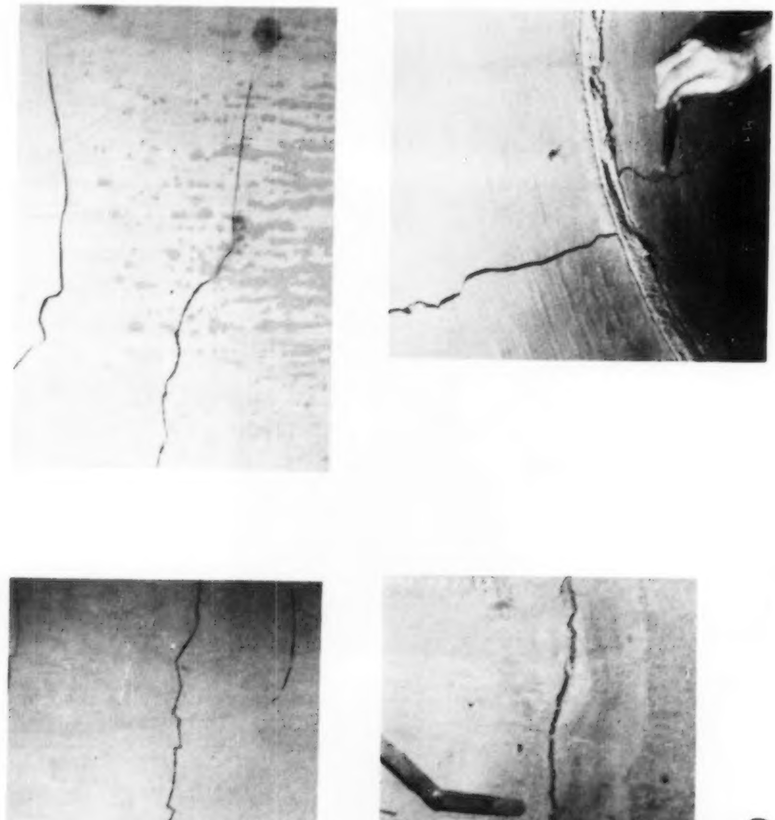


PLATE D

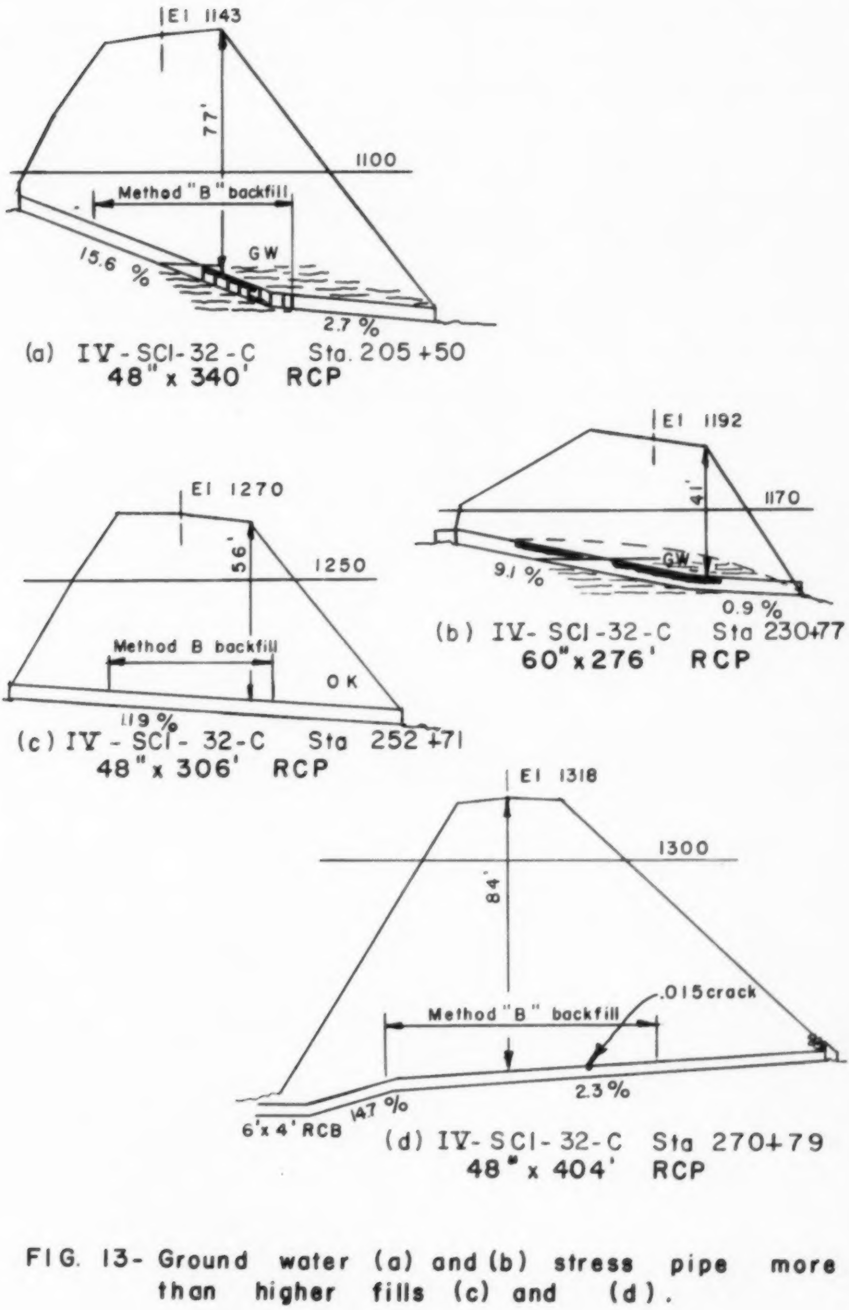


FIG. 13- Ground water (a) and (b) stress pipe more than higher fills (c) and (d).

as a "safety valve" in case of failure of underdrains.

The greatest distress in a box culvert had been repaired, but the writer had measured deformation on a previous inspection. This was a 6x6-ft box section under a 63-ft overfill distressed near the outfall where fill varied from 18 to 35 ft. One 30-ft section between joints was deformed on both walls and both slabs, with shear offsets up to 5 in. The trouble was diagnosed as "hard foundation", this section having subsided much less than the adjoining sections. Method B backfill had been specified, but it is not a substitute for uniform bedding. The good condition of the box under the higher part of the overfill justifies the basic design.

It was concluded from observation of performance that Method B backfill is correct in principle and practical in application to rigid culverts under high overfills, but that inspection must be unusually alert because of the tremendous loads which may be shifted back to the structure by careless construction. It is just as important for design to foresee interference between Method B backfill and construction of large earth embankments and to consider the relative economy of a heavier structure installed by classical methods.

The foregoing account of design and performance of rigid culverts under high overfills refers to practice of the California Division of Highways, but opinions and conclusions are those of the writer and not necessarily those of the Division. The review was made jointly with M. G. Spangler, M. ASCE, of Iowa State College, assisted by John G. Hendrickson, A.M. ASCE, Research Engineer, American Concrete Pipe Association, and C. W. W. Abbott, A.M. ASCE, Associate Bridge Engineer, California Division of Highways. Mr. George T. McCoy, M. ASCE is State Highway Engineer and the writer is Bridge Research Engineer, under the immediate direction of F. W. Panhorst, M. ASCE, Assistant State Highway Engineer, Bridges. Acknowledgment is also made to Messrs. Abbott and Hendrickson and to Edwin R. Rowe, J. M. ASCE, for photographs used to illustrate the oral presentation at the Highway Division Meeting at San Diego.

DIAMETER (in.)	METHOD A Standard	METHOD A Special	METHOD B Standard	METHOD B Special
12	36	62	Inf	
24	27	51	Inf	
36	25	52	Inf	
48	23	53	Inf	
60	23	48	32*	Inf
72	23	45	28*	Inf
84	23	37	27*	90
96	20	33		59
108	20	33		48

* Prefer stronger pipe under ordinary backfill.

"Special" commercial pipe is "standard" or "thick wall" with extra steel for specified D-load strength.

Table I - Abstract from table of maximum overfill in feet for commercial R C pipe